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Meteorology Research, Inc., Altadena, CA

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A Project MISTT Report

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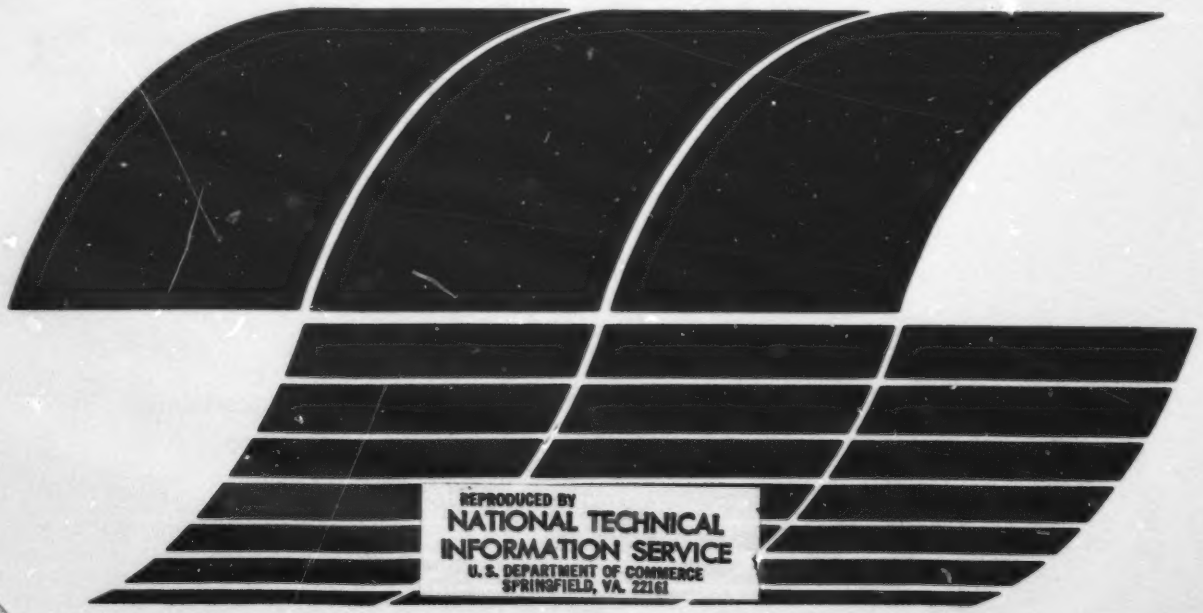

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Airborne measurements of aerosols and pollutant gases in urban and power plant plumes were conducted during July 1976 in the vicinity of St. Louis, Missouri. The measurements, performed as part of Project MISTT, were designed to characterize the physical and chemical behavior of these plumes under a variety of meteorological conditions. The airborne data were analyzed to gain a better understanding of the factors affecting the transport, transformation, and removal of primary and secondary pollutants, particularly those containing sulfur.

The field program and experimental techniques are described, and the results and conclusions of the analyses of the airborne measurements and meteorological data are presented.

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St. Louis Area, July 1976
A Project MISTT Report

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ABSTRACT

Airborne measurements of aerosols and pollutant gases in urban and power plant plumes were conducted during July, 1976, in the vicinity of St. Louis, Missouri. These measurements, performed as part of Project MISTT, were designed to characterize the physical and chemical behavior of these plumes under a variety of meteorological conditions. Analyses of the aircraft data were directed towards gaining a better understanding of the factors affecting the transport, transformation, and removal of primary and secondary pollutants, particularly those containing sulfur.

Conditions were found to be favorable for the long-range (>300 km) transport of SO_2 in stable power plant plumes aloft on over half of the nights in July, 1976. One such plume was sampled 75 km downwind of the plant, at which distance a peak SO_2 concentration of over 0.85 ppm was measured. This behavior is markedly different from that observed during the day, when increased vertical mixing caused a rapid dilution of the plume.

Analyses of the physical and chemical properties were primarily conducted by other members of the Project MISTT team. Among the results of these analyses summarized in this report are that:

- SO_2 conversion rates ranged from 1 to 4 percent per hour at midday to less than 0.5 percent per hour at night;
- Submicron aerosol size distributions were found to be bimodal, with a nuclei mode below 0.05 μm diameter and an accumulation mode in the diameter range 0.05 to 1.0 μm;
- Nucleation rates in the plume from the Labadie power plant ranged from 1700 $cm^{-3}s^{-1}$ to 1 $cm^{-3}s^{-1}$, depending on the time of day and distance from the source. The aerosol volume going into the nuclei mode from gas-to-particle conversion was about 5 percent of the volume which went directly into the accumulation mode, and this fraction was independent of the nucleation rate;
- Enhanced ozone levels in a power plant plume (relative to background) were observed on at least two days during July, 1976. This enhancement was observed only during daytime when the plume was very dilute (peak SO_2 concentrations < 50 ppb).

This report was submitted in fulfillment of Contract 68-02-2411 by Meteorology Research, Inc. under the sponsorship of the U. S. Environmental Protection Agency. This report covers a period from June, 1976 to December, 1977 and work was completed December, 1977.

CONTENTS

Abstract iii
Figures vi
Tables vii
Acknowledgment viii

1. Introduction 1
2. Summary of Results and Conclusions 5
    Results 5
    Conclusions 10
3. Program Description 12
4. Experimental Methodology 17
    Aircraft Description 17
    Flight Plans 18
    Calibration 18
    Data Processing 20
5. Meteorological Analyses 21
    Summary of Meteorological Conditions 21
    Description of Analyses 27
    Case History Analysis-18 July 1976 28

References 37
Project MISTT Bibliography 39

FIGURES

Number		Page
1	Example of ozone bulge in Labadie Power Plant Plume	9
2	Traverse flight pattern for plume sampling	19
3	Cross Section of SO_2 concentrations (ppm) in the Labadie plume made from sampling traverses between 1525 and 1600 CDT at 25 km downwind (ground level 150 m)	29
4	Isopleths of constant wind speed as a function of height (m msl) and time (CDT) for 1900 CDT 18 July to 0900 CDT 19 July 1976	30
5	Cross section of SO_2 concentrations (ppm) in the Labadie plume made from sampling traverses between 2107 and 2233 CDT at 25 km downwind	31
6	Cross section of SO_2 concentrations (ppm) in the Labadie plume made from sampling traverses between 2246 and 2318 CDT at 50 km downwind	33
7	SO_2 concentration at 760 m msl at downwind distances of 25, 50, and 75 km for traverses made north of the plant in Labadie plume between 2225 and 2400 CDT, 18 July 1976	34

TABLES

Number		Page
1	Project MISTT Participants.	3
2	Urban Plume Sampling Summary.	14
3	Labadie Plume Sampling Summary.	15
4	Meteorological Summary	22

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SECTION 1

INTRODUCTION

In order to formulate effective air pollution control strategies, it is necessary to understand the physical and chemical properties of the pollutants to be controlled. One pollutant of particular interest is sulfur, because of its potential adverse effects on human health, vegetation, materials, and visibility. The long-range transport and transformation of sulfur compounds in the atmosphere has been the subject of numerous investigations. One major program, conducted under the direction of the USEPA, is Project MISTT (Midwest Sulfur Transformation and Transport). Project MISTT was a multi-year team project involving numerous research groups. This report describes research performed by Meteorology Research, Inc. (MRI) as part of MISTT in 1976.

The principal objective of the MRI sampling programs was to characterize the physical and chemical behavior of plumes (both urban and power plant) under a variety of meteorological conditions. Particular areas of interest were to

- measure primary and secondary pollutant mass fluxes in the plume at a number of distances downwind of the source, and
- characterize plume behavior during daytime (well-mixed) and nighttime (stable) regimes.

As part of Project MISTT, MRI performed airborne measurements downwind of urban and industrial sources of sulfur dioxide. Analyses of the aircraft data were directed towards gaining a better understanding of the factors affecting the transport, transformation, and removal of primary and secondary pollutants, particularly those containing sulfur. Among these factors were temperature, solar radiation, humidity, vertical mixing, wind velocity, background pollutant concentrations, and trace element (catalyst) concentrations.

Preliminary measurements for Project MISTT began in 1973, followed by large-scale field programs in 1974, 1975, 1976, and 1977. This report is concerned with the 1976 program; descriptions of the other programs are

presented in White et al (1976) and Ogren et al (1978a). The 1976 field program was designed to provide additional information on long-range plume transport (> 200 km), plume behavior at night, and changes in the physical and chemical properties of plumes during the early morning transition period. Most of the measurements in 1976 were made in the plume of the coal-fired Labadie power plant near St. Louis, Missouri.

The primary aerosol sampling platform for the work performed under this contract was an instrumented Cessna 206, operated by MRI. Measurements obtained by the Cessna 206 included SO_2, NO, NO_x, O_3, light-scattering coefficient (b_{SCAT}), condensation nuclei, aerosol charge acceptance, aerosol size distributions, temperature, dewpoint, pressure, and position. The aircraft was equipped to collect aerosol samples for elemental and chemical analyses using cascade impactors and a size-segregating sequential filter sampler, as well as hydrocarbon samples in stainless steel canisters. Data from the instruments, as well as several status indicators, were recorded on magnetic tape cartridges approximately once per second.

Several other mobile sampling platforms were employed during the July 1976 field program to support and complement the Cessna 206. These included a Rockwell Grand Commander instrumented to measure SO_2, O_3, b_{SCAT}, condensation nuclei, aerosol charge acceptance, pressure, and position, as well as collect aerosol filter samples for sulfate analysis (operated by Washington University); a Piper Cherokee equipped with a correlation spectrometer (COSPEC) for measurements of SO_2 and NO_2 overhead burdens (operated by Environmental Measurements, Inc.); a C-45 aircraft equipped with a downward-looking LIDAR system for remote sensing of the plume at night (operated by EPA-Las Vegas); and a mobile van equipped to measure most of the parameters measured by the Cessna 206 (operated by the University of Minnesota). A separate relay aircraft was also operated by Washington University to allow long-range communications among the sampling aircraft, ground-based units, and the operations headquarters at Washington University.

Project MISTT was a multi-year effort involving a team of several research groups. Organizations that participated in Project MISTT are listed in Table 1, along with a brief description of their responsibilities. Overall program direction was provided by the Environmental Sciences Research Laboratory of the U. S. Environmental Protection Agency at Research Triangle Park, North Carolina. The field programs in the St. Louis area were coordinated by Washington University.

TABLE 1. PROJECT MISTT PARTICIPANTS

Airborne Research Associates:	Electric Field Measurements, Scout Aircraft.
Argonne National Laboratory:	Boundary Layer Structure and Dynamics, Dry Deposition Rates. (ANL work was co-sponsored by ERDA.)
Battelle Columbus Laboratories:	Outdoor Smog Chamber Measurements of Sulfate Formation Rates in St. Louis, Gas Chromatographic--Mass Spectrometric Measurements of Organic Vapors.
California Institute of Technology:	Development of a Supersensitive Sulfate Measurement Technique, Sulfate Measurements--1974.
Crocker Nuclear Laboratory (University of California, Davis):	Aerosol Sample Analysis using IEXE techniques.
Environmental Measurements, Inc.:	COSPEC Measurements.
Environmental Quality Research:	Forecasting and other Meteorological Support, Dry Deposition Studies.
EPA-Las Vegas:	Helicopter Measurements, Winter 1976, Aircraft Lidar Observations, Summer 1976.
EPA-Research Triangle Park:	Program Management, Instrument Calibration, Data Transfer, Measurements in EPA Mobile Lab.
Florida State University:	Aerosol Measurements Using the FSU "Streaker" Sampler with PIXE Analysis.
IIT Research Institute:	Optical and Electron Microscopy.
Meteorology Research, Inc.:	Aircraft Measurements, Data Analysis, Meteorological Interpretation.
University of Minnesota:	Aerosol Size Distribution Measurements, Aerosol Dynamics, Ground Measurements, Data Analysis, and Interpretation.
Northrop Services, Inc.:	Instrument Calibration, Program Coordination--1977.
Rockwell International Science Center:	Pilot Balloon Operations.
Stanford Research Institute:	Ground-Mobile Lidar Operations.
University of Texas:	Effects of Charge on Aerosol Deposition, Reactive Plume Models.
Washington State University:	Detailed Hydrocarbon Analysis, Interpretation of Ozone and Hydrocarbon Data.
Washington University:	Field Program Direction, Scout Aircraft Operations, Data Analysis and Interpretation, Data Management and Model Development, Sulfate Determinations.
University of Washington:	Ground-Based Measurements and Data Interpretation, Sulfate Species Measurement, Air Mass Trajectories.

This report describes the field program conducted during July 1976 in the St. Louis area. The emphasis is to describe the work done by MRI in the field, including experimental techniques, and to summarize the results and conclusions of analyses of the aircraft data. In addition, the results of detailed meteorological analyses performed by MRI are presented.

SECTION 2

SUMMARY OF RESULTS AND CONCLUSIONS

RESULTS

Airborne sampling was performed by MRI on sixteen days during the July 1976 MISTT field program. Approximately 70 percent of the sampling hours were devoted to measurements of the coal-fired Labadie power plant plume, with the remaining time spent characterizing the urban plume of St. Louis. Data from these flights were processed to final form (calibrated and verified) by MRI, and supplied to the other program participants for use in their analyses. This section summarizes both the results of analyses performed by MRI and the results of analyses performed by other investigators using data collected by MRI. The analyses primarily emphasize the behavior of power plant plumes; a discussion of the results of Project MISTT related to urban plumes can be found in Ogren et al (1978a).

Plume Transport

Meteorological analyses by Smith et al (1978) revealed that conditions in the St. Louis area were favorable for the long-range transport of SO_2 in stable plumes aloft on at least eighteen of the thirty-one nights in July 1976. The mechanism for such transport was the formation of stable layers (> 400 m agl) with high wind speeds. These "jets" occurred after the nighttime surface radiation inversion had formed, effectively isolating the plume from the surface. Under such conditions, during the night a plume could travel nearly 300 km from the source with relatively little dilution enroute. Separation of the plume from the surface would eliminate the surface removal mechanism for SO_2, thereby enhancing the potential for high ground level SO_2 concentrations far from the source when the radiation inversion is destroyed by solar heating the following morning and the plume is ventilated to the ground.

Even without long-range transport, conditions were favorable almost every night during the July sampling program for the trapping of stable high concentration plumes in elevated layers. Thus, the nighttime regime is also important for the accumulation of sulfur in the atmosphere and for the multiday buildup of sulfur compounds in an air mass.

In contrast to the nighttime regime, conditions during the midday were characterized by strong vertical mixing and rapid dilution of the plume. As a consequence, long-range plume transport (i.e., greater than 200 km) at concentrations >10 to 20 ppb was not observed during the day. Plumes emitted in the afternoon tended to rise higher than plumes emitted at other times, due to the neutral or slightly unstable conditions typical of that time.

Pollutant Transformations

Analyses of the pollutant transformation mechanisms affecting the plume from the coal-fired Labadie power plant were primarily performed by investigators at Washington University and the University of Minnesota. Their results, which are based in part on data collected by the Cessna 206, are summarized below.

1. The conversion rate of SO_2 to $SO_4^=$ ranged from 1-4 percent per hour at midday to less than 0.5 percent per hour at night. Excess particulate sulfur in the plume (i.e., above background) correlated with excess light scattering by particles in the plume, indicating that most of the particulate sulfur was formed in the light scattering size range (nominally 0.1-1 μm diameter). The dry removal rate for sulfur in plumes from tall stacks is greatest at midday, when the strongest vertical mixing occurs (Husar et al, 1978).

2. Dry deposition velocities for sulfur dioxide were 1.5-2.0 cm s^{-1} during the day for two of the days studied (Gillani, 1978).

3. The ratio of particulate sulfur to total sulfur in the plume (gaseous plus particulate) was correlated with the total dosage of solar radiation, i.e., the amount of radiative solar energy received by the plume (Gillani et al, 1978). For the two days analyzed, linear correlation coefficients (r^2) were 0.85 and 0.92.

4. Aerosol size distributions were measured in both the plume and the surrounding background air mass. Characterization of these distributions was done in terms of two additive log-normal functions: one describing nuclei less than 0.05 μm diameter, and the second describing accumulation mode aerosol between 0.05 and 1.0 μm.

On the average, results show that distribution of the nuclei volume for aerosol size less than 0.05 μm in both plume and background can be paramaterized with a geometric mean size of 0.021 $\pm$ 0.005 μm and a geometric standard deviation of 1.5 $\pm$ 0.1. Total nuclei volume was found to be about 1 percent of total submicron aerosol volume. For aerosols larger than 0.05 μm, the geometric mean size of aerosol volume distributions in the plume was found to be 0.18 $\pm$ 0.02 μm. This is significantly different from the 0.23 $\pm$ 0.01 μm measured for background air. The dispersion of the distribution in this size range, measured by a geometric standard deviation of 1.92 $\pm$ 0.04, does not change significantly from in-plume to background. Integral aerosol volume concentrations, however, varied greatly from as much as 90 μm^3 cm^{-3} in the plume to 4 μm^3 cm^{-3} in the background, depending on the meteorology and time of day measurements were taken (Cantrell and Whitby, 1978).

5. Nucleation rates in the Labadie plume ranged from 1700 $cm^{-3} s^{-1}$ at 0630 near the plant to values near 1 $cm^{-3} s^{-1}$ when the plume was well-mixed at some distance from the plant, and at night. Nucleation rates in background air ranged from 2-4 $cm^{-3} s^{-1}$ during the day to 0.7 $cm^{-3} s^{-1}$ at night. The aerosol volume going into the nuclei mode from gas-to-particle conversion was about 5 percent of the volume which went directly into the accumulation mode, and was independent of the nucleation rate (Whitby et al, 1978).

6. The ratio of the rate of aerosol volume formation to average plume SO_2 concentration ranged from 9 to 130 μm^3 $cm^{-3} hr^{-1} ppm^{-1}$ for the two days analyzed in detail. There are indications that this ratio increases with increasing distance from the stack, which suggests a change in the dominant precursors resulting in aerosol formation as the plume becomes more dilute (Whitby et al, 1978).

7. The total aerosol number concentration (NT) and the number concentration in the accumulation mode (Na) was found to be

$$NT \approx 10 (Na)^{0.904}$$

This relationship was observed to hold for both plume and background air (Whitby et al, 1978).

8. Nuclei concentrations in the plume can be correlated with ultraviolet radiation for the two days analyzed. Nuclei concentrations increased as ultraviolet radiation increased (Cantrell and Whitby, 1978).

9. Estimated SO_2 conversion rates for a daytime plume under relatively uniform meteorological conditions show a significant increase with plume age up to two hours: 0.4 $\pm$ 0.2 percent per hour in the first hour and 1.1 $\pm$ 0.4 percent per hour in the second. In a night-to-day transition period during which the mixing height was rising (with resultant enhanced rate of dilution in the plume), the conversion rate was constant at 0.5 $\pm$ 0.2 percent per hour for the first two hours in the atmosphere. Insufficient measurements have been obtained to permit extension of these results to plume ages greater than two hours (Cantrell and Whitby, 1978).

10. A net production of ozone within the Labadie plume was observed on two of the sampling days. On 9 July 1976, an increase in ozone from about 60 ppb in the background to 110 ppb in the plume was reported by Gillani et al (1978).

On 18 July 1976, a similar (although less pronounced) ozone bulge was observed 25 km downwind of the Labadie plant by the MRI aircraft (Figure 1). In this case, the bulge represented a 10 ppb increase over the 50 ppb background ozone level. Strong plume dilution was observed along with the ozone bulge; peak plume SO_2 concentrations were about 50 ppb.

Plume NO concentrations were virtually the same as in background air, however, a rise in NO_2 concentration of 5-10 ppb was observed in the plume along with the ozone bulge. Although uncertainties in the zero of the NO/NO_x analyzer prevent verification of the consistency of the O_3 /NO/NO_2 concentrations with the photostationary state (Leighton, 1961), the small rise in the NO_2/NO ratio along with the O_3 bulge supports the claim that the measured ozone bulge was real and not just an artifact of the data.

Ozone formation in power plant plumes has been a major area of investigation for researchers at the University of Maryland (Davis et al, 1974). Their results indicated that the following conditions are conducive to ozone production in the plume (Keifer, 1977):

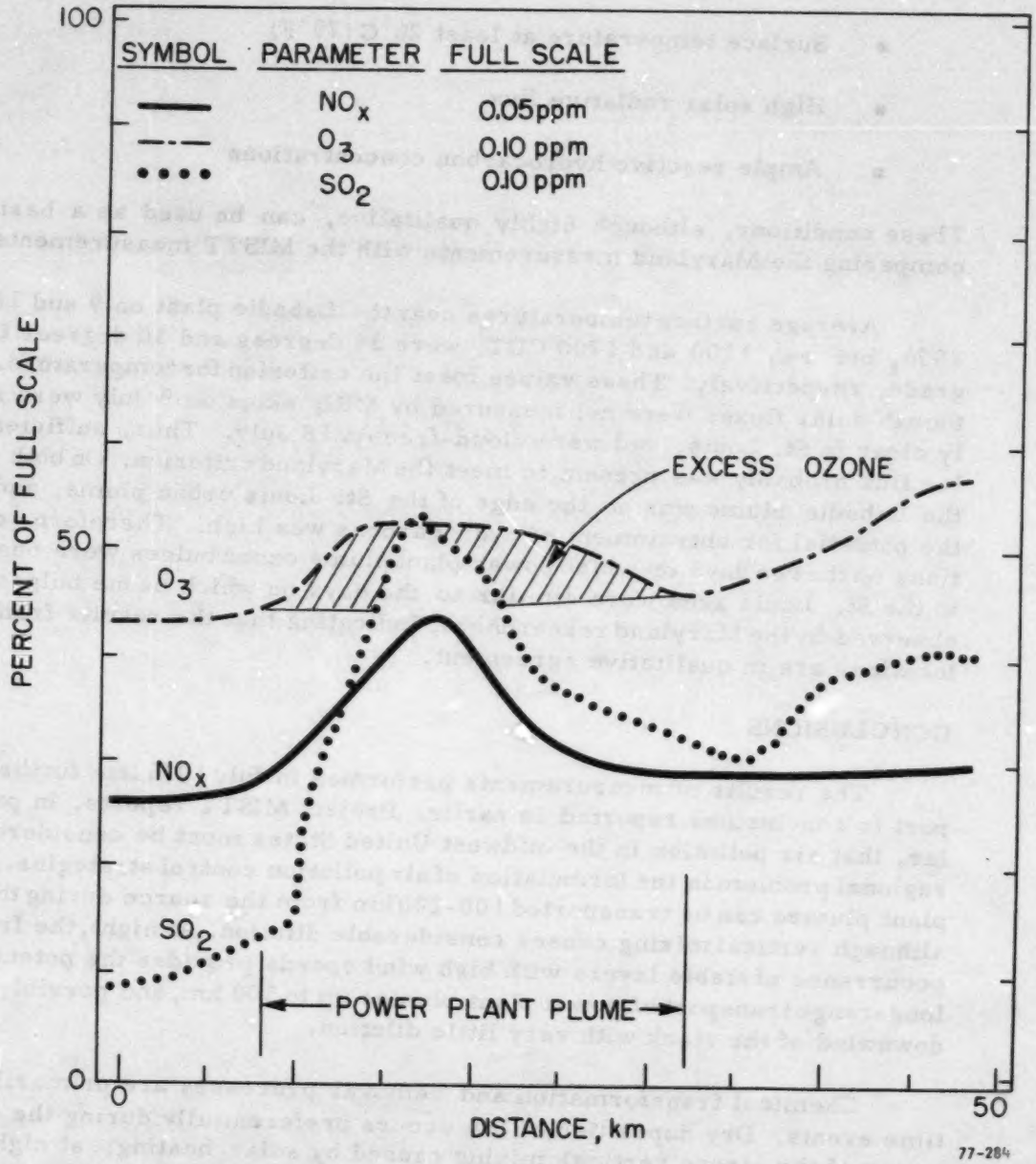

Figure 1. Example of Ozone Bulge in Labadie Power Plant Plume. Data collected on 18 July 1976 at 1540 CDT, 25 km downwind of plant. Traverse elevation 910 m msl, ground elevation 140 m msl.

- Surface temperature at least 26°C (79°F)
- High solar radiative flux
- Ample reactive hydrocarbon concentrations

These conditions, although highly qualitative, can be used as a basis for comparing the Maryland measurements with the MISTT measurements.

Average surface temperatures near the Labadie plant on 9 and 18 July 1976, between 1100 and 1700 CDT, were 34 degrees and 30 degrees Centigrade, respectively. These values meet the criterion for temperature. Although solar fluxes were not measured by MRI, skies on 9 July were mostly clear in St. Louis, and were cloud-free on 18 July. Thus, sufficient solar flux probably was present to meet the Maryland criterion. On both days, the Labadie plume was on the edge of the St. Louis urban plume, and thus the potential for entrainment of hydrocarbons was high. Therefore, conditions on the two days on which power plant plume ozone bulges were observed in the St. Louis area were similar to the days on which ozone bulges were observed by the Maryland researchers, indicating that the results from both locations are in qualitative agreement.

CONCLUSIONS

The results of measurements performed in July 1976 lend further support to conclusions reported in earlier Project MISTT reports, in particular, that air pollution in the midwest United States must be considered as a regional problem in the formulation of air pollution control strategies. Power plant plumes can be transported 100-200 km from the source during the day, although vertical mixing causes considerable dilution. At night, the frequent occurrence of stable layers with high wind speeds provides the potential for long-range transport of power plant plumes up to 300 km, and possibly more, downwind of the stack with very little dilution.

Chemical transformation and removal processes are primarily daytime events. Dry deposition of SO_2 occurs preferentially during the day because of the strong vertical mixing caused by solar heating; at night, formation of the surface radiation inversion effectively decouples the plume from the ground. The conversion of SO_2 to $SO_4^=$ proceeds more rapidly during the day than at night. Measurements made during July 1976 can be used to support the contention that the primary aerosol formation mechanism involves photochemical reactions, however, other potential mechanisms cannot

be excluded from consideration. The sulfate that is formed from SO_2 conversion is found in the particle size range that contributes most to light scattering by particles; hence, sources of SO_2 can be important contributors to visibility reduction by aerosols. This contribution generally occurs far removed from the source because of the long time needed to oxidize SO_2.

Finally, power plants are capable of increasing ozone levels above background values downwind of the stack. Ozone bulges in power plant plumes can be observed under certain conditions; specifically, when the plume is very dilute, solar radiation is present, temperatures are high, and reactive hydrocarbons are present.

SECTION 3

PROGRAM DESCRIPTION

The July 1976 MISTT field program was conducted in the vicinity of St. Louis, Missouri. Flight operations were based at the Spirit of St. Louis Airport, while technical direction during sampling missions and planning and debriefing meetings took place at the operations headquarters at Washington Unisity.

Both urban and coal-fired power plant plume sampling missions were performed. The Labadie power plant, located 55 km west of the St. Louis Gateway Arch, was the subject of the power plant plume measurements. This plant, rated at about 2400 megawatts gross load, was chosen because of its large size and because the plume from its 200 m stacks is generally distinct from the St. Louis urban plume. Moreover, measurements in this plume provided continuity for measurements made in the 1974 and 1975 MISTT field programs. Urban plume measurements were performed downwind of St. Louis. This plume was chosen for study in order to provide continuity with previous measurement programs, and because it is a relatively isolated plume located in flat terrain. In addition, the presence of the Regional Air Pollution Study (RAPS) sampling network provided additional support for the MISTT program.

The program was a team effort involving researchers from EPA-ESRL, Washington University, University of Minnesota, Washington State University, Environmental Measurements, Inc., EPA-Las Vegas, and Environmental Quality Research, as well as MRI. The field calibration system for the gaseous monitors on the aircraft was supplied by EPA-ESRL, which also provided technical direction for the project and on-site data processing facilities. Washington University provided the second instrumented aircraft, relay aircraft, and operations headquarters facilities. The aerosol size distribution measurement system on the MRI Cessna 206 was maintained by the University of Minnesota, which also operated an instrumented van to study ground-level plume impact. Correlation spectrometer (COSPEC) measurements were performed from an aircraft operated by Environmental Measurements, Inc., while the aircraft-based LIDAR system used to help locate the plume at night was operated by EPA-Las Vegas. Hydrocarbon sample analyses were performed by Washington State University. Meteorological support (forecasting and winds aloft measurements) was provided by Environmental Quality Research. Descriptions of the work performed by these other team members can be found in the sources listed in the Bibliography.

The contribution of MRI to the field program was the operation of the Cessna 206 sampling aircraft. Plume measurements were performed by MRI between 1 July and 30 July 1976. A total of thirty-three sampling flights were made by the 206, covering sixteen of the thirty days during the period. Approximately 70 percent of the total flight time was devoted to power plant plume measurements and 30 percent to urban plume measurements. Summaries of the MRI urban and coal-fired power plant plume sampling missions are presented in Tables 2 and 3.

TABLE 2. URBAN PLUME SAMPLING SUMMARY

Date (1976)	Flight Times (CDT) Start	Flight Times (CDT) Stop	Tape Cartridge Number	Approx. Plume Sampling Dist. (km)	No. of Sulfate Samples	No. of Impactor Samples	No. of HC Samples	Comments
6/30	0920	1240	601	25	3	--	--	
7/2	0830	1140	603	33	5	--	--	Urban plume with a few local stacks
7/2	1250	1640	604	65, 80	6	--	--	Some rain at start of flight
7/7	0850	1250	609	25, 35, 40, 60, 65	13	--	3	
	1405	1820	610	35, 60, 65, 70	14	--	3	
7/23	0930	1420	626	45, 75, 90, 110	10	--	4	In coordination with Da Vinci project
	2305	0305	627	350, 375, 430	7	--	4	In coordination with Da Vinci project
7/24	0400	0510	628	480	3	--	1	In coordination with Da Vinci project
	0510	0800	629	480, 550, 570	6	--	2	In coordination with Da Vinci project
	1200	1530	631	420,350, 300, 250	5	--	--	In coordination with Da Vinci project

TABLE 3. LABADIE PLUME SAMPLING SUMMARY

Date (1976)	Flight Times (CDT) Start	Flight Times (CDT) Stop	Tape Cartridge Number	Approx. Plume Sampling Dist. (km)	No. of Sulfate Samples	No. of Impactor Samples	No. of HC Samples	Comments
6/29	1140	1240	600	9, 18	2	--	--	Systems checkout
7/1	0810	1145	602	5, 7, 8, 18	5	--	--	
7/5	1040	1450	605	5, 8, 17, 26	5	--	3	
	1545	1940	606	45	2	--	1	
	2025	0005	607	35, 70	6	--	--	
7/6	0115	0505	608	135, 140, 155	6	--	--	
7/12	1340	1640	611	5, 13, 35, 50	8	3	2	Light rain at end of flight in plume
7/14	0555	1010	613	25, 40, 50	9	4	4	
	1100	1430	614	5, 50, 60	3	2	1	
7/15	0810	≈1200	616	5, 35, 50, 60	6	4	3	
	1330	1540	617	5, 55	2	2	2	
7/18	0725	0930	619	25	5	2	2	
	1445	≈1900	620	30, 35, 75	4	3	1	
	2040	0045	621	30, 45, 50, 55, 80	5	3	4	
7/20	1040	1420	622	15, 25, 45, 65	10	2	3	
	1520	1935	623	80, 130, 175	11	3	3	
	2058	0130	624	130, 155, 175, 195, 215	6	--	2	
7/23	0430	0830	625	20, 30	14	--	5	

TABLE 3 (Continued)

Date (1976)	Flight Times (CDT) Start	Flight Times (CDT) Stop	Tape Cartridge Number	Approx. Plume Sampling Dist. (km)	No. of Sulfate Samples	No. of Impactor Samples	No. of HC Samples	Comments
7/26	0415	0815	632	17, 45	4	3	3	
7/27	1055	1210	634	20, 27	2	1	1	Cross-comparison with COSPEC
7/28	0410	0805	635	20, 55, 63, 70	16	2	1	EPA-Las Vegas LIDAR system used for plume detection
	0955	1305	636	25, 30	12	1	3	Cross-comparison with COSPEC
7/30	0520	0910	637	20, 27, 30, 33	14	2	6	
	≈1130	≈1530	638	15, 20, 25, 35, 40, 45	15	3	5	

SECTION 4

EXPERIMENTAL METHODOLOGY

Operations of the MRI sampling aircraft were coordinated closely with participants in the program. Key elements in the coordination scheme included technical direction by radio from senior investigators at the operations headquarters (OHQ), long-range communications capabilities provided by relay aircraft located between the sampling area and OHQ, and frequent planning meetings and mission debriefing sessions.

In general, the two heavily instrumented aircraft (Cessna 206 and Rockwell Grand Commander) were used to complement each other while the other two sampling aircraft (COSPEC and LIDAR measurement systems) were used as scouts. The Cessna 206 sampled at slower speeds and measured a greater number of pollutant and meteorological parameters, while the Grand Commander was capable of high-speed sampling and was equipped with a high-sensitivity SO_2 monitor. Accordingly, one mode of operations was to use the Cessna 206 for detailed near-source (within ~ 100 km) plume characterizations, while the Grand Commander attempted to track the plume as far from the source as possible, performing less detailed plume characterizations at more widely spaced distances downwind. The other general mode of operations was to use the two aircraft sequentially to allow plume sampling for extended periods of time (24 hours or more). In this mode, one aircraft would sample while the crew of the other aircraft rested and prepared for the next mission.

The experimental methodology related to the operation of the Cessna 206 is described in this chapter. Additional information on experimental methodology can be found in White et al (1976), Ogren et al (1978a), and Blumenthal et al (1978). Descriptions of the experimental methods used by other program participants, as well as the manner in which the various sampling platforms were coordinated by the operations headquarters, can be found in the references in the Project MISTT bibliography (Page 39).

AIRCRAFT DESCRIPTION

An instrumented Cessna 206 was used as the primary sampling platform for aerosol measurements. The 206 instrumentation for this contract

was similar, with slight refinements, to that used during earlier MISTT programs. A detailed discussion of the Cessna 206 airborne sampling system can be found in Blumenthal et al (1978).

FLIGHT PLANS

The basic flight plans for both urban and power plant plumes consisted of a combination of constant-altitude traverses flown through the plume perpendicular to its longitudinal axis* and vertical spirals (soundings) flown over a given point. These patterns allowed a detailed characterization of the plume at a particular downwind distance. In addition, horizontal traverses were flown outside the plume to characterize the background environment (Figure 2).

After the plume was located at the desired downwind distance, ground reference points were chosen to allow traverse paths approximately perpendicular to the plume axis. The 206 then made a number of traverses between the endpoints at various altitudes. The number of traverses at each downwind distance depended on the vertical extent of the plume, but was usually at least three, and sometimes five or more.

Following the plume traverses, a spiral was usually made as close to the plume centerline as possible. This spiral extended from as near the ground as possible to well above the plume (power plants) or mixing layers (urban plumes). This completed the plume characterization at that distance, and the aircraft then moved downwind and repeated the process. While transiting between downwind distances, the aircraft flew outside the plume and performed background measurements.

CALIBRATION

Calibrations were performed by MRI personnel using a system provided by EPA. A discussion of this system and calibration procedures is included in Blumenthal et al (1978).

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* - It should be noted that it was frequently difficult to ensure that a given traverse was normal to the plume's longitudinal axis due to plume wandering, and because the plume was essentially invisible except for near-stack sampling traverses.

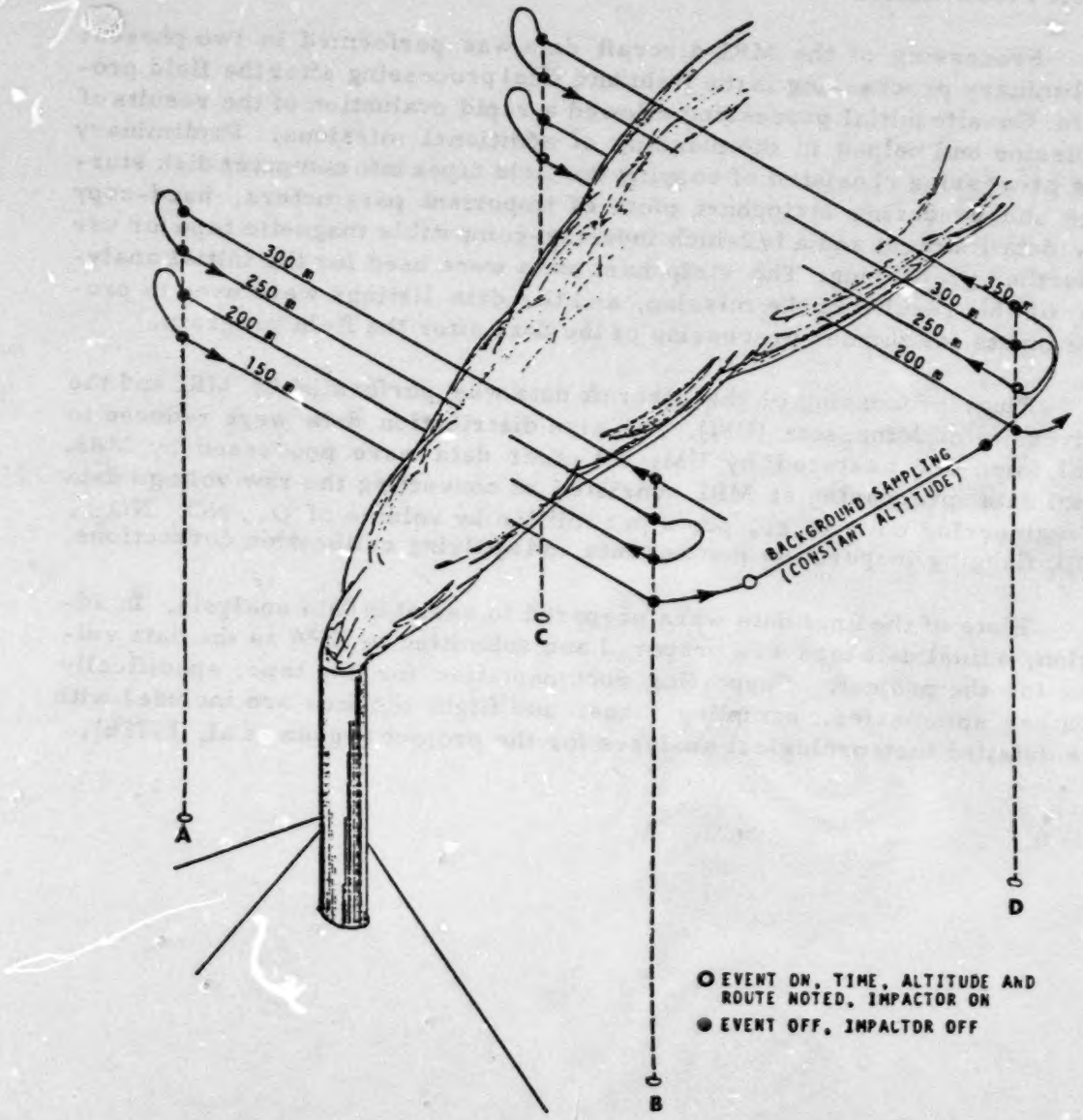

Figure 2. Traverse flight pattern for plume sampling. Points A, B, C, and D are readily identifiable ground reference points which are determined to allow traverse paths perpendicular to the plume axis.

DATA PROCESSING

Processing of the MRI aircraft data was performed in two phases: preliminary processsing in the field and final processing after the field program. On-site initial processing allowed a rapid evaluation of the results of a mission and helped in the planning of additional missions. Preliminary data processing consisted of copying the field tapes into computer disk storage and producing stripchart plots of important parameters, hard-copy raw data listings, and a 1/2-inch industry-compatible magnetic tape for use in further processing. The stripchart plots were used for the initial analysis of the results of the mission, and the data listings were used to provide inputs for further processing of the data after the field program.

Final processing of the aircraft data was performed by MRI and the University of Minnesota (UM). The size distribution data were reduced to final form and analyzed by UM; all other data were processed by MRI. Final data processing at MRI consisted of converting the raw voltage data to engineering units (e.g., parts per million by volume of O_3, NO, NO_x, SO_2), flagging inoperative instruments and applying calibration corrections.

Plots of the final data were prepared to assist in data analysis. In addition, a final data tape was prepared and submitted to EPA as the data volume for the project. Supporting documentation for this tape, specifically weather summaries, sampling maps, and flight outlines are included with the detailed meteorological analyses for the project (Ogren et al, 1978b).

SECTION 5

METEOROLOGICAL ANALYSES

A firm understanding of the meteorological factors affecting plume behavior was the goal of analyses performed by MRI for the 1976 MISTT program. In addition, meteorological conditions on several days selected for analysis by other MISTT program participants were documented in detail as part of the MRI analyses.

SUMMARY OF METEOROLOGICAL CONDITIONS

The storm track during the month of July 1976 was located over the Canadian - United States border, which is its normal location for July. To the south, over the central and eastern portion of the country, the weather was governed by migrating high-pressure cells, or ridges, moving from west to east. Occasionally a cold front extended south from the storm track, but the fronts were weak and either turned stationary over Iowa or the Gulf Coast or dissipated entirely.

The high-pressure ridges were primarily responsible for changes in stability temperature advection, flow direction, and, consequently, plume behavior. The position of the ridge and the location of its axis were found to exert the primary influence on mixing heights, stability, and winds in the sampling region. All five sampling periods selected for detailed analysis occurred either underneath or to the west of an existing or building high pressure center aloft.

Measurable rainfall fell in St. Louis on six of the thirty-one days in July. A trace of precipitation was reported at St. Louis during the sampling period of 5-6 July. All other periods analyzed in detail were characterized by clear to partly cloudy weather with no rainfall within the sampling area.

Meteorological conditions during the sampling period are summarized in Table 4. The table utilizes RAPS temperature soundings and pibal data available every six hours to determine stability, wind and temperature characteristics in the layer from the surface to 1800 meters AGL. Except where otherwise stated, the information listed is derived from RAPS Station 142 near the Labadie power plant. All wind directions are in true degrees and wind speeds are in meters per second.

TABLE 4. METEOROLOGICAL SUMMARY

Date	Time (CDT)	Boundary Layer (Surface to ≈1800 m AGL) Conditions During Previous Six Hours			
		General Stability Type	Wind Dir/Vel	Temp (C°)	(%) Cloud Coverage
6/29/76	0500	Stratified-stable, Precipitation	245/6	+20	100
	1100	Slightly mixed, becoming Well mixed-capped	260/11	+21	70
	1700	Well mixed-capped, Precipitation	275/10	+20	85
	2300	Stratified-stable	325/13	+14	35
6/30/76	0500	Stratified-stable	330/11	+12	0
	1100	Slightly mixed, becoming Well mixed-capped	325/9	+12	30
	1700	Well mixed-capped to Unstable	325/7	+14	65
	2300	Well mixed-capped becoming Stratified-stable	345/6	+14	15
7/01/76	0500	Stratified-stable	355/3	+14	0
	1100	Slightly mixed, becoming Well mixed-capped	300/2	+15	0
	1700	Well mixed-capped	210/2	+18	70
	2300	Well mixed-capped becoming Stratified-stable	210/6	+17	50
7/02/76	0500	Stratified-stable	220/8	+16	65
	1100	Slightly mixed, rapidly to Unstable	205/9	+16	95
	1700	Unstable, Precipitation	180/7	+14	100
	2300	No Data Available	--	--	100
7/03/76	0500	No Data Available	--	--	100
	1100	No Data Available	--	--	100
	1900*	Well mixed-capped	060/7	+15	100
	2300	No Data Available	--	--	100
7/04/76	0700*	Stratified-stable	060/8	+14	80
	1100	No Data Available	--	--	50
	1900*	Unstable	025/8	+15	65
	2300	No Data Available	--	--	40
7/05/76	0500**	Stratified-stable	025/6	+17	0
	1100**	Unstable	010/5	+18	0
	1700**	Unstable, Precipitation	360/8	+19	15
	2300**	Well mixed-capped	055/9	+18	35

* - Salem, Illinois
** - RAPS 141 (Downtown St. Louis)

TABLE 4 (Continued)

Date	Time (CDT)	Boundary Layer (Surface to ≈1800 m AGL) Conditions During Previous Six Hours			
		General Stability Type	Wind Dir/Vel	Temp (C°)	(%) Cloud Coverage
7/06/76	0500	Stratified-stable	055/5	+16	0
	1100	Unstable	035/4	+17	0
	1700	Unstable	005/2	+20	25
	2300	Well mixed-capped, becoming Stratified-stable	275/4	+19	25
7/07/76	0500	Deep-stable to Stratified-stable	260/10	+18	0
	1100	Stratified-stable, becoming Slightly mixed	260/8	+19	35
	1700	Unstable	240/10	+22	25
	2300	Well mixed-capped, Precipitation	260/15	+21	90
7/08/76	0500	Stratified-stable	295/11	+19	40
	1100	Slightly mixed, becoming Well mixed-capped	310/3	+20	5
	1700	Unstable	265/3	+23	20
	2300	Unstable, becoming Stratified-stable	255/7	+22	60
7/09/76	0500	Stratified-stable	240/8	+20	20
	1100	Slightly mixed	225/7	+21	45
	1700	Slightly mixed	210/6	+23	20
	2200	No Data Available	230/10	--	0
7/10/76	0700*	Stratified-stable	260/8	+25	0
	1100	No Data Available	--	--	0
	1900*	Slightly mixed, to Well mixed-capped	245/7	+24	0
	2300	No Data Available	--	--	0
7/11/76	0700*	Deep-stable, to Stratified-stable	275/12	+22	0
	1100	No Data Available	--	--	30
	1900*	Well mixed-capped	255/8	+23	60
	2300	No Data Available	--	--	20
7/12/76	0500	Stratified-stable	295/12	+21	10
	1100	Slightly mixed, becoming Well mixed-capped	310/7	+23	10
	1700	Well mixed-capped, with Unstable and Precipitation	330/4	+23	50

* - Salem, Illinois

TABLE 4 (Continued)

Date	Time (CDT)	Boundary Layer (Surface to ≈1800 m AGL) Conditions During Previous Six Hours			
		General Stability Type	Wind Dir/Vel	Temp (C°)	(%) Cloud Coverage
7/12/76 (Con't)	2300	Stratified-stable	315/4	+23	90
7/13/76	0500	Stratified-stable	340/5	+20	85
	1100	Slightly mixed, becoming Well mixed-capped	275/4	+22	55
	1700	Well mixed-capped	250/3	+24	35
	2300	Stratified-stable	245/8	+24	5
7/14/76	0500	Deep-stable to Stratified-stable	270/9	+23	0
	1100	Slightly mixed, becoming Well mixed-capped	270/6	+24	0
	1700	Unstable	245/3	+26	20
	2300	Stratified-stable	255/9	+24	10
7/15/76	0500	Stratified-stable	250/10	+23	30
	1100	Well mixed-capped, becoming Unstable	270/9	+22	65
	1700	Unstable, Precipitation	250/12	+22	70
	2300	Well mixed-capped	265/9	+18	70
7/16/76	0500	Stratified-stable, becoming Slightly mixed	305/10	+17	95
	1100	Well mixed-capped	330/8	+16	35
	1700	Well mixed-capped	320/6	+18	5
	2300**	Well mixed-capped, becoming Stratified-stable	335/7	+15	0
7/17/76	0500	Stratified-stable	345/7	+14	0
	1100	Well mixed-capped	325/4	+14	0
	1700	Well mixed-capped	305/3	+17	95
	2300	Well mixed-capped, becoming Stratified-stable	305/3	+17	35
7/18/76	0500	Stratified-stable	255/2	+16	0
	1100	Well mixed-capped	165/4	+17	0
	1700	Well mixed-capped	190/4	+22	0
	2300	Stratified-stable	190/6	+18	0

** - RAPS 141 (Downtown St. Louis)

TABLE 4 (Continued)

Date	Time (CDT)	Boundary Layer (Surface to ~1800 m AGL) Conditions During Previous Six Hours			
		General Stability Type	Wind Dir/Vel	Temp (C°)	(%) Cloud Coverage
7/19/76	0500	Stratified-stable	220/7	+19	0
	1100	Well mixed-capped	200/5	+20	50
	1700	Well mixed-capped	190/4	+23	70
	2300	Well mixed-capped, becoming Stratified-stable	210/9	+21	60
7/20/76	0500	Stratified-stable	235/13	+20	25
	1100	Stratified-stable	240/9	+22	25
	1700	Well mixed-capped, to Unstable	220/7	+25	90
	2300	Well mixed-capped, becoming Stratified-stable	240/12	+23	25
7/21/76	0500	Stratified-stable	265/12	+21	95
	1100	Slightly mixed, becoming Well mixed-capped	260/7	+22	80
	1700	Unstable	240/5	+24	35
	2300	Well mixed-capped, Precipitation	250/9	+22	85
7/22/76	0500	Stratified-stable, becoming Well mixed-capped	255/11	+22	100
	1100	Well mixed-capped, becoming Unstable	265/9	+24	100
	1700	Unstable	240/8	+27	85
	2300	Unstable, becoming Stratified-stable	235/11	+26	20
7/23/76	0500	Stratified-stable	245/10	+22	0
	1100	Well mixed-capped, becoming Unstable	265/5	+23	0
	1700	Unstable	280/4	+26	25
	2300	Unstable, becoming Stratified-stable	300/5	+31	5
7/24/76	0500	Stratified-stable	290/10	+24	0
	1100	Well mixed-capped	310/6	+25	0
	1700	Well mixed-capped	345/7	+25	30
	2300	Stratified-stable	035/7	+21	65

TABLE 4 (Continued)

Date	Time (CDT)	Boundary Layer (Surface to ≈1800 m AGL) Conditions During Previous Six Hours			
		General Stability Type	Wind Dir/Vel	Temp (C°)	(%) Cloud Coverage
7/25/76	0500	Stratified-stable	035/6	+20	0
	1100	Well mixed-capped	040/4	+21	0
	1700	Well mixed-capped	085/3	+24	35
	2300	Well mixed-capped, becoming Stratified-stable	150/7	+21	0
7/26/76	0500	Stratified-stable	210/8	+21	0
	1100	Well mixed-capped	245/7	+24	0
	1700	Well mixed-capped	265/1	+27	5
	2300	Unstable, Precipitation, becoming Stratified-stable	240/6	+24	85
7/27/76	0500	Stratified-stable	235/10	+24	100
	1100	Well mixed-capped, to Unstable	215/7	+23	65
	1700	Unstable, Precipitation	200/5	+23	90
	2300	Unstable, to Stratified-stable	205/8	+23	45
7/28/76	0500	Stratified-stable	235/13	+23	0
	1100	Well mixed-capped, becoming Unstable	250/9	+23	5
	1700	Unstable, Precipitation	255/5	+25	35
	2300	Unstable, Precipitation, becoming Stratified-stable	295/6	+23	100
7/29/76	0500	Stratified-stable, to Well mixed-capped	245/5	+20	50
	1100	Well mixed-capped	275/4	+20	100
	1700	Well mixed-capped	060/2	+21	65
	2300	Stratified-stable	135/4	+21	30
7/30/76	0500	Stratified-stable	220/6	+20	0
	1100	Well mixed-capped	285/6	+22	55
	1700	Well mixed-capped, to Unstable	215/4	+24	90
	2300	Unstable, to Stratified-stable	230/12	+24	65

The six basic "stability types" depicted are:

- "Deep Stable" -- Stable lapse rates extending from the surface through at least 1000 meters.
- "Stratified Stable" -- One or more stable layers in between neutral layers.
- "Slightly Mixed" -- Lapse rates are between isothermal and adiabatic with surface heating causing some vertical eddies.
- "Well Mixed" -- Lapse rates are nearly adiabatic through a deep layer (at least 1000 meters)
- "Unstable" -- Adiabatic or superadiabatic lapse rates, considerable vertical motion.
- "Precipitation" -- Rain occurring presently or within past two hours. Precipitation widespread enough to have affected plume configuration.

DESCRIPTION OF ANALYSES

Two types of meteorological analyses were performed: routine analyses for each sampling day and detailed analyses for selected days. Included in the routine meteorological analyses are synoptic weather maps, forward and back air mass trajectories (twice daily), and summary tables of temperature, dewpoint, cloud cover, wind speed and direction, and stability. These analyses, along with flight maps and sampling summaries, are included as Part A of the detailed meteorological analyses for the project (Ogren et al, 1978b).

Several days were selected for detailed analyses by the principal investigators for Project MISTT. These days were selected based on the particular meteorological conditions and plume configuration encountered, and the validity and completeness of data obtained by the aircraft. The days analyzed in detail are 5, 6, 9, 10, 14, 18, 23 and 24 July 1976. Analyses included in-depth evaluation of the synoptic and mesoscale factors affecting the plume, and calculation of plume trajectories for most sampling runs

made by the MRI Cessna 206 and Washington University Rockwell Grand Commander. These analyses were supplied to the other program participants for use in their analyses of the aircraft data. Part B of the meteorological analyses (Ogren et al., 1978b) contains discussions of the synoptic and mesoscale meteorological conditions as well as the results of plume trajectory analyses for the days listed above.

Case History Analysis-18 July 1976

One important result of the detailed meteorological analyses was an understanding of the potential for long-range transport of elevated plumes at night. A case history analysis of the plume measurements obtained on 18 July 1976 was presented by Smith et al (1978). Excerpts from that paper are included here to illustrate the meteorological factors which create the potential for long-range transport at night and inhibit it during the day.

On 18 July 1976, the St. Louis area, along with much of the eastern United States was under the influence of a large, dry, high pressure system. During the afternoon, the temperature lapse rate was adiabatic and strong thermal mixing existed. However, since the relative humidity at the surface was only 35 percent, no clouds developed. Winds aloft were southerly at about 4-6 m/s from the surface to 900 m above mean sea level (msl), shifting slightly southwesterly and decreasing to about 3 m/s from 900-2000 m msl. The light daytime winds caused slow transport of the effluent along the plume centerline. Although transport was slow, strong mixing rapidly dispersed the plume both vertically and horizontally as the pollutants moved downwind. The daytime SO_2 plume was well mixed from the surface to greater than 1400 m msl and had a maximum measured concentration of 60 ppb at 25 km.

Figure 3 is a cross section of the daytime plume SO_2 concentration between 1520 and 1608 Central Daylight Time (CDT) 25 km downwind of the plant (about 2-1/2 hours travel). This figure, as well as Figures 5 and 6, was constructed from horizontal traverses perpendicular to the plume axis. It is not a "snapshot," but a composite constructed from data collected by the Cessna 206 aircraft.

To draw the contours, instantaneous data values (one each two seconds or ~60 m) were superimposed on the traverse path (dashed lines). Using these values to fix the location of contour lines at each traverse, smooth contours were extrapolated, based on meteorological constraints and an approximate match of the flux from the power plant. Contours outside the traverse range and those which intersect only one level are presented as dashed lines to clearly indicate the extrapolation.

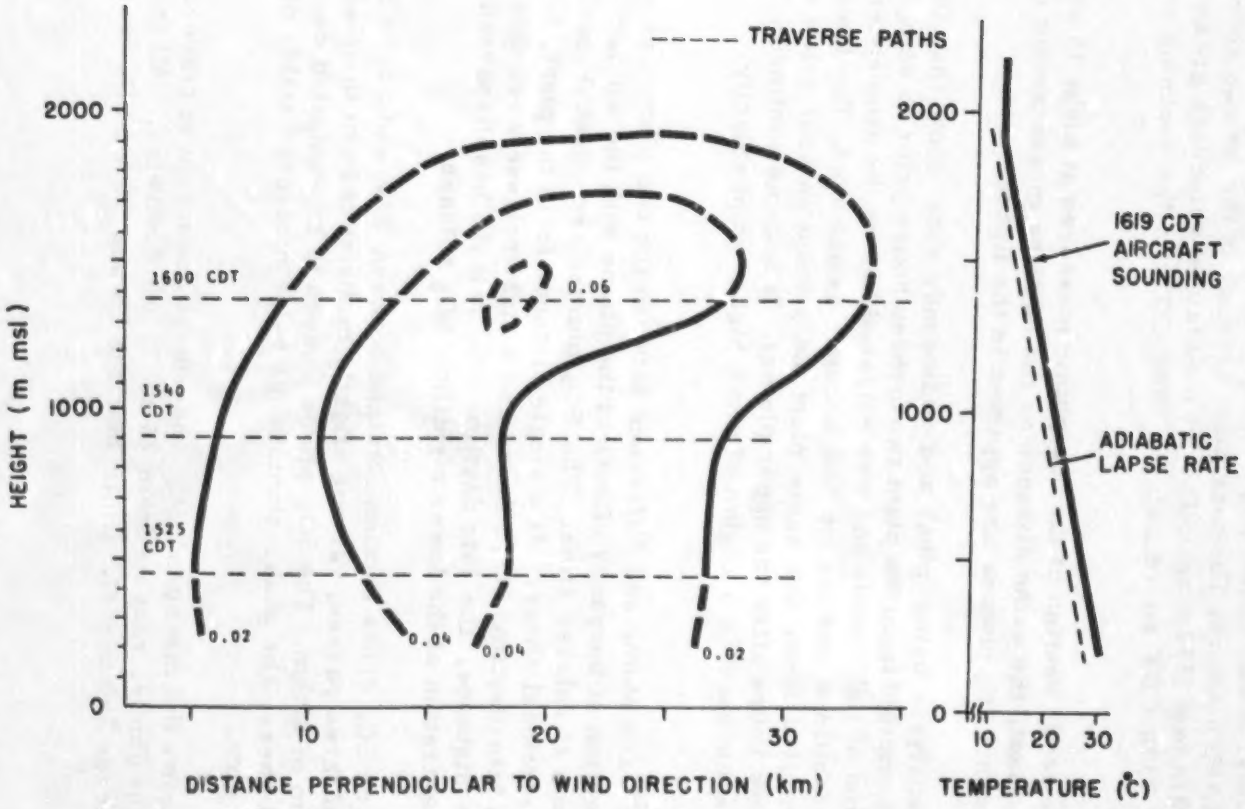

Figure 3. Cross section of SO_2 concentrations (ppm) in the Labadie plume made from sampling traverses between 1525 and 1600 CDT at 25 km downwind (ground level 150 m). Contours outside the traverse range and those which intersect only one level are represented as dashed lines to indicate extrapolations.

In the evening, a surface radiation inversion formed, thermally driven mixing ceased, and the lapse rate aloft became more stable. Although winds at the surface were less than 4 m/s during the night, a low level jet gradually formed aloft. Figure 4 shows a time-altitude cross section of wind speed for the night of 18 July. It was constructed from radiosonde data taken from Station 142 of the RAPS network. The maximum velocity in the jet was about 15 m/s at about 520 m msl (350 m agl). The jet maintained velocities greater than 12 m/s from 2300 CDT on 18 July to 0800 CDT on the morning of 19 July.

Figure 5 is a cross section of the SO_2 plume measured at night 25 km downwind from the plant, the same distance as the daytime measurement of Figure 3. Two distinct SO_2 plumes are apparent in the figure.

Trajectory analysis using pibal and radiosonde data show that the upper one had been emitted from the plant two to three hours prior to sampling. It is in a region of light winds and was released before the atmosphere had become well stabilized and the jet had become established. The lower SO_2 plume was emitted from the same plant, only about an hour prior to sampling (one to two hours after the upper plume). It became confined in a more stable atmosphere and in a region of much higher wind velocity.

The height of each plume and difference between the two plumes is attributable to interaction of buoyancy effects of the plume with the wind speed and stability regime at release time. The SO_2 plumes are offset from one another due to directional shear. At a single distance from the plant, both the remnants of a late-daytime SO_2 release and a night release were detected. At the same distance, the late daytime SO_2 release has dispersed to one-half the concentration of the lower nighttime SO_2 release.

Figure 6 is an SO_2 cross section obtained between 2246 and 2318 CDT that is made up of three passes, varying slightly in distance from the plant, but all within 5 km of 50 km. The SO_2 plume is seen to be elongated due to slight directional shear. The peak instantaneous value measured at this distance exceeded 1 ppm.

Figure 7 shows the measured SO_2 concentrations for three traverses in the stable night plume, ranging from 25 to 75 km downwind. All three traverses were made 760 m msl. (Note that the 25 and 50 km SO_2 traces

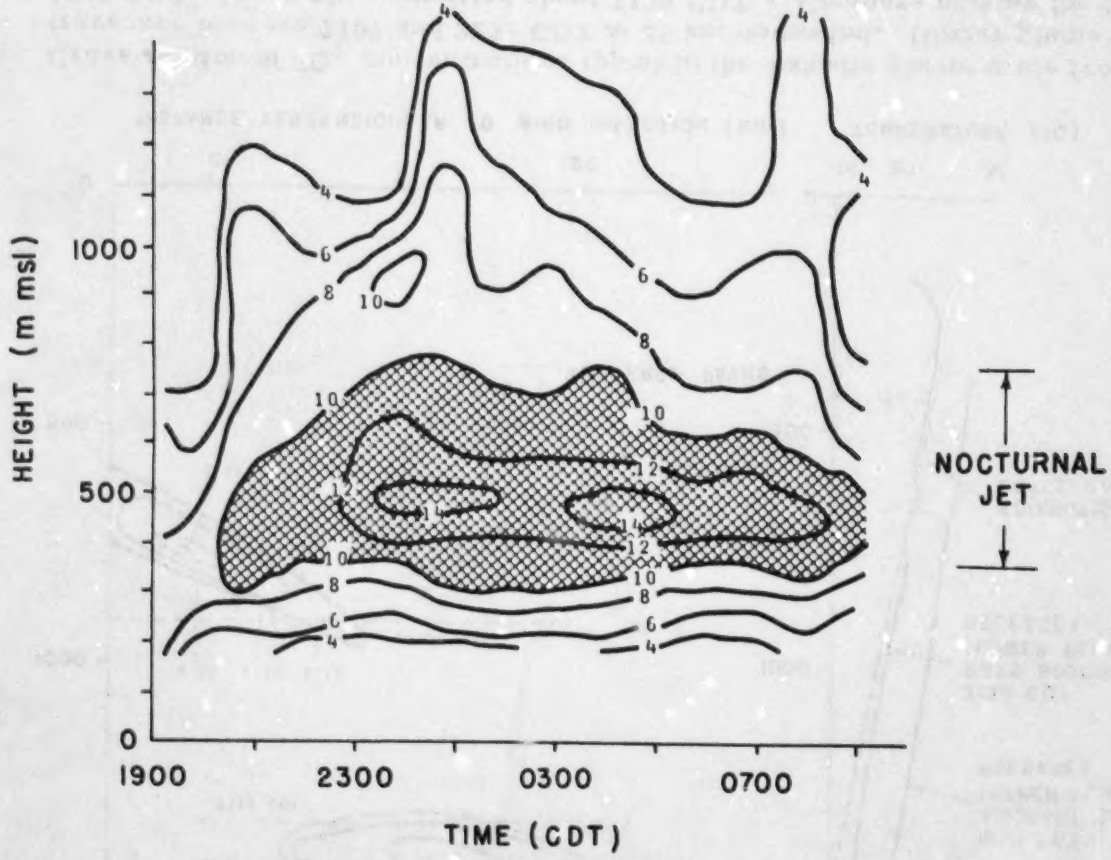

Figure 4. Isopleths of constant wind speed as a function of height (m msl) and time (CDT) for 1900 CDT 18 July to 0900 CDT 19 July 1976. (Speeds in m/s, ground level 150 m.) Plotted from RAPS Data, Station 142 ~ 15 km northeast of Labadie Plant.

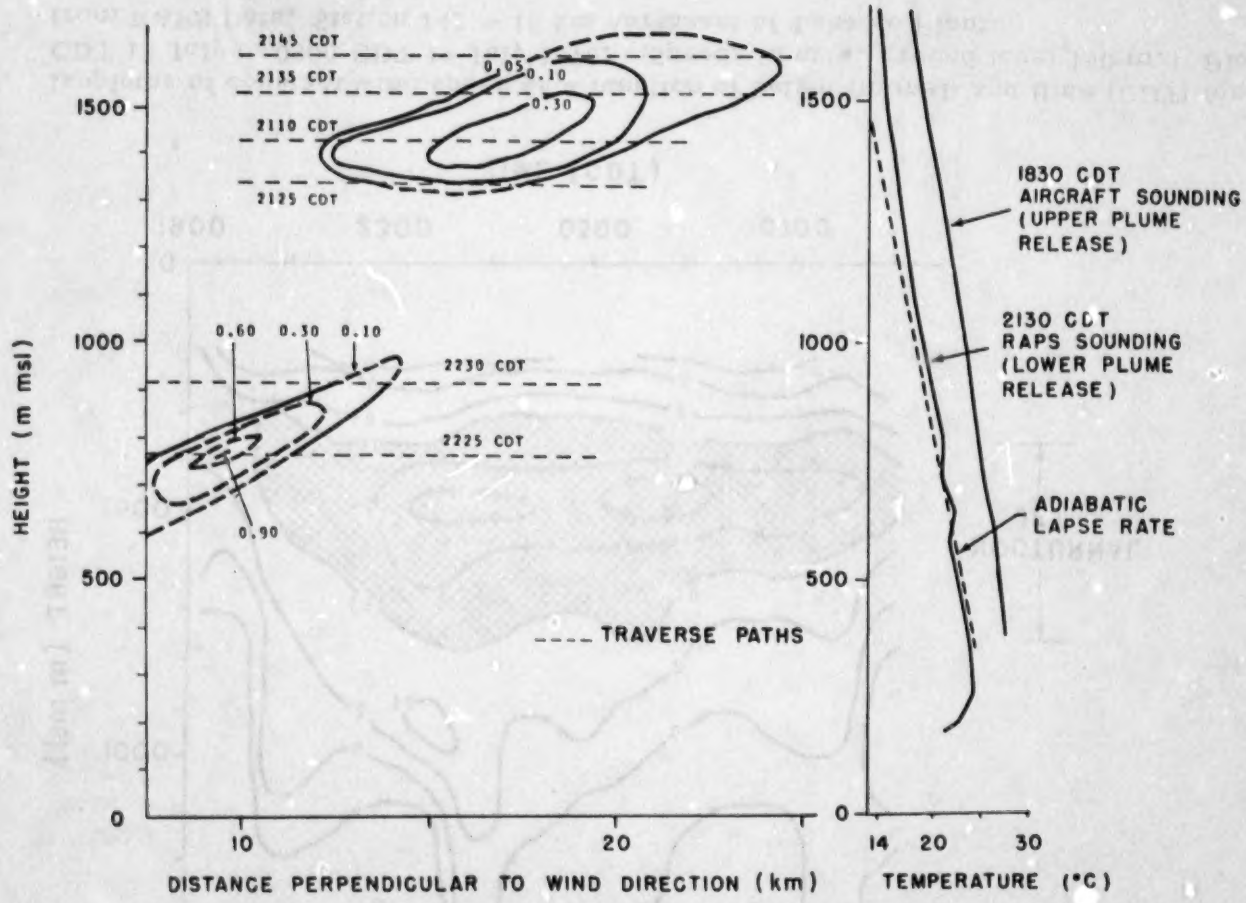

Figure 5. Cross section of SO_2 concentrations (ppm) in the Labadie plume made from sampling traverses between 2107 and 2233 CDT at 25 km downwind. (Upper plume emitted about 1900 CDT; lower plume emitted about 2130 CDT.) Contours outside the traverse range and those which intersect only one level are represented as dashed lines to indicate extrapolations.

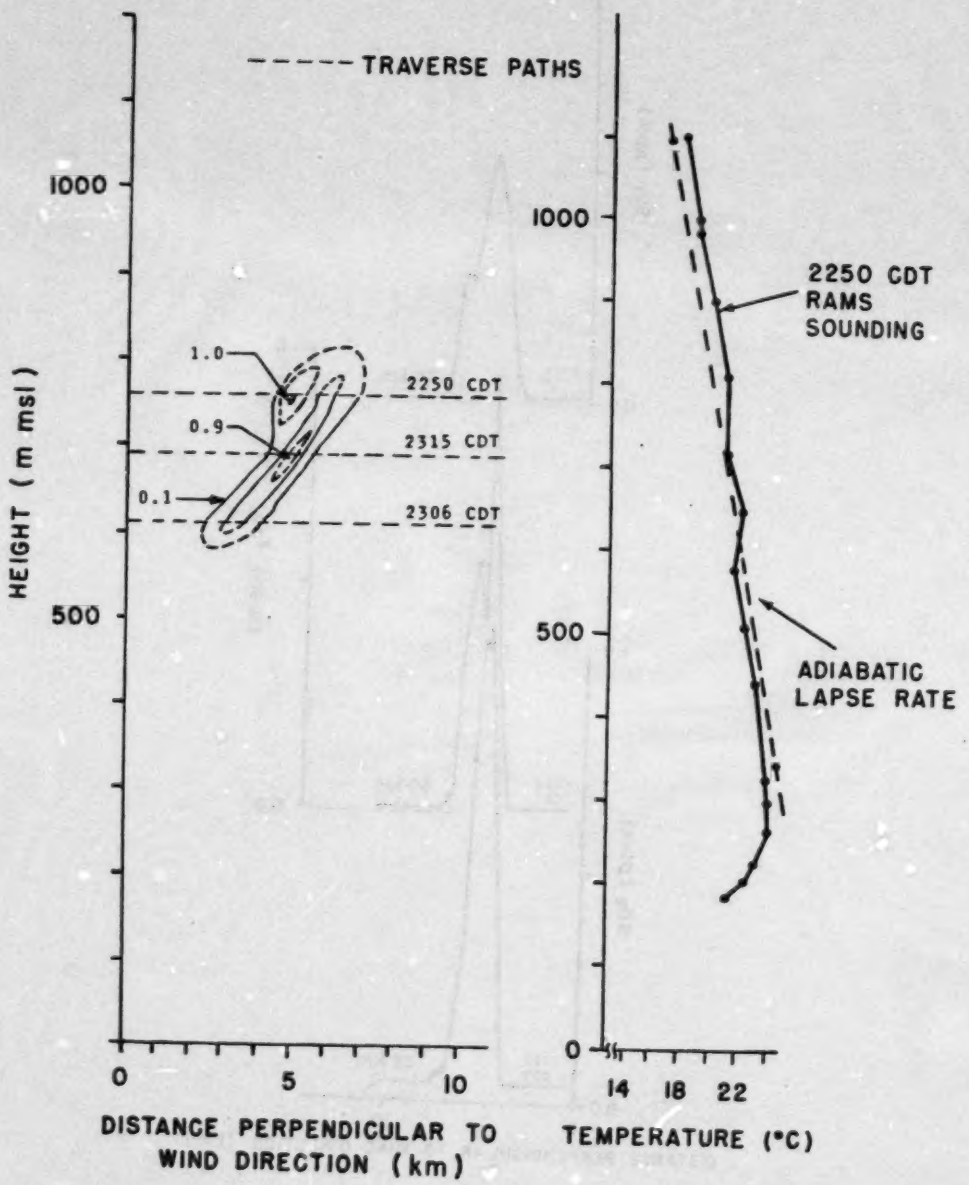

Figure 6. Cross section of SO_2 concentrations (ppm) in the Labadie plume made from sampling traverses between 2246 and 2318 CDT at 50 km downwind. (The plume was emitted around 2150 CDT.) Contours outside the traverse range and those which intersect only one level are represented as dashed lines to indicate extrapolations.

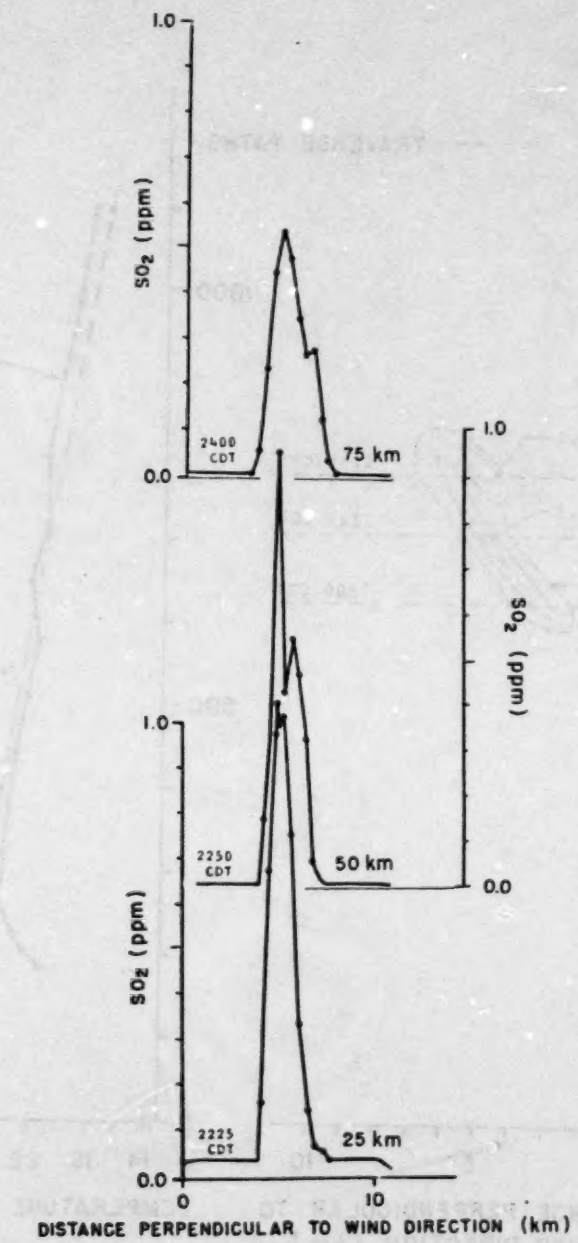

Figure 7. SO_2 concentration at 760 m msl at downwind distances of 25, 50, and 75 km for traverses made north of the plant in Labadie plume between 2225 and 2400 CDT, 18 July 1976.

are the data used for the contour levels at 760 m in Figures 5 and 6, respectively.) At 75 km, the SO_2 concentration in Figure 7 still exceeded 0.5 ppm, and an orbit at 75 km indicated a maximum concentration of over 0.85 ppm. The SO_2 is seen to remain very concentrated with little dilution after after initial buoyancy effects have dissipated prior to 25 km.

Even with the high wind speeds, mixing was minimal. A good indicator of mixing is the turbulence measured in the aircraft. The aircraft turbulence probe indicated between 0.5 and 1 $cm^{2/3}$ sec^{-1} in the plume. For comparison, "light" turbulence (i.e., barely noticeable) registers 2 to 3 $cm^{2/3}$ sec^{-1} (MacCready, 1966).

Although the stable, concentrated SO_2 plume shown in Figure 7 was not actually followed farther than 75 km, the wind data in Figure 4 suggest that much greater transport was likely. From Figure 4, at 760 m msl, the wind speed remained about 10 m/s (36 km/hr) until 0400 CDT, and then averaged at least 8 m/s (29 km/hr) until 0600 CDT. Four hours of additional transport at 10 m/s and two hours at 8 m/s would put the plume at a downwind distance of about 275 km by 0600 CDT. Although the wind data in Figure 4 were obtained near the plant, the synoptic meteorology of the 18th and pilot balloon data taken downwind during the night suggest that the vertical wind structure was not appreciably different over the potential 275 km distance.

The measured concentration data show a dramatic contrast between day and night dispersion and transport of SO_2. During the day the SO_2 became vertically well mixed through the mixing layer. With relatively constant wind direction and minimal shear the SO_2 plume maintained its identity. The light daytime wind contributed little to long distance transport. During the day, the SO_2 plume mixed to the ground, allowing removal of SO_2 by deposition. As the stable night conditions set in and wind speeds above the ground level increased, the residual daytime SO_2 plume became decoupled from the ground and was transported with little dilution over long distances.

The SO_2 emitted at night remained decoupled from the ground and experienced much less dilution. High concentrations of SO_2 and other pollutants were transported up to 300 km before daytime, reaching the ground the next morning. The SO_2 in these night plumes is isolated from deposition and is thus available for conversion to sulfate at least during the night and into the next morning.

Sampling on other days showed that, as solar heating eroded the radiation inversion, these stable plumes were mixed to the ground and added to surface SO_2 concentrations over 200 km from their source. Stable plumes

of this type have also been reported to impact on high terrain at night, causing extensive vegetation damage (Long and Williams, 1977).

Blackadar (1957, 1976) has indicated that nocturnal low-level jets, such as the one which occurred on 18 July 1976, are a common occurrence over much of the world. He has shown that the jets are a result of interaction between the geostrophic wind field and the radiationally induced daily cycle of the turbulence intensity in the boundary layer.

In July, 1976, conditions in the St. Louis area were favorable for the long-range transport of SO_2 in stable plumes aloft on at least eighteen out of thirty-one nights. On at least three different occasions, power plant plumes were actually tracked to distances greater than 200 km during the night and early morning hours. The nighttime regime thus provides a mechanism for the transport of SO_2 from a single source over a synoptic scale region.

Even without long-range transport, conditions were favorable almost every night during the July sampling program for the trapping of stable high concentration plumes in elevated layers. Thus, the nighttime regime is also important for the accumulation of sulfur in the atmosphere and for the multiday buildup of sulfur compounds in an air mass.

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